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The coherent point drift algorithm adapted for fixtureless metrology of non-rigid parts

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Abstract

Unlike the metrology of rigid parts, no viable and industrial solutions in the case of non-rigid parts are available. Due to gravity load and residual stress, non-rigid parts (flexible, compliant) may have in a Free State condition a significant different shape than their corresponding nominal geometry (CAD model). As a result, very expensive and specialized fixtures mounting are needed by the industry to constrain the component during the inspection. Dealing with this real industrial problem, this paper proposes a new method to inspect non-rigid parts without these specialized fixtures. In this method, the CAD model is smoothly modified to fit the scanned part respecting two criteria that belong to non-rigid parts. The first criterion is the isometric transformation (or the condition that stretch should be very small) between the original CAD model and the modified one. The second criterion is the Euclidian distance between the modified CAD model and its corresponding scanned part. The proposed approach consists of adapting the Coherent Point Drift powerful non rigid registration method to meet the specifications of non-rigid parts. In other words, by minimizing the two above criteria, the paper proposes a 'flexible' registration to align the scanned manufactured compliant part to its nominal model in order to compare them and to deliver an inspection report. Satisfying results were obtained when validating the proposed method on a case study taken from the aerospace industry. The low percentage of error between the estimated value of defect and the reference one reflect the effectiveness of the proposed approach.

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Keywords: geometric inspection; dimensionnal inspection; registration; GD&T; fixtureless; flexible part; tolerancing

1. Introduction

Geometric and dimensional tolerance standards, such as ASME Y14.5 or ISO GPS assume inspections of manufactured mechanical parts are carried out in a Free State condition [1, 2]. This is an inappropriate assumption when dealing with non-rigid parts such as thin wall parts used in automotive and aerospace industries. Due to gravity effect and residual strain, these parts may have, in a Free State condition, a significantly different form comparable to their nominal model. Specialized fixtures are then needed to constrain these non-rigid parts during the inspection process. Fig.1 shows a typical aircraft skin panel mounted and conformed on a representative jig causing substantial costs for industry. For instance, the preparation time to inspect this panel is around 60 man-hours. That is why fixtureless quality control of non-rigid parts has become a challenging task in the transport industry.

This subject has been studied by many researchers and an exhaustive review has been provided in [3]. The state of the art in machine vision inspection research and technology has been presented by Malamas *et al.* [4]. Ravishankar *et al.* [5] proposed a rigid registration method for non-contact inspection of freeform surfaces by matching shapes based on the modified Iterative Closest Point (ICP) method to define a criterion for the acceptance or rejection of a part. Weckenmann *et al.* [6] as well as Jaramillo *et al*. [7] proposed an approach based on a finite element method to obtain a physical deformation of the original CAD model, and radial basis functions to approximate this deformation faster and in real time, opening the door to on-line inspection of deformable parts. In 2010, Abenhaim *et al.* [8] proposed the Iterative Displacement Inspection (IDI) algorithm by iteratively

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deforming smoothly the CAD mesh until it matches the scanned part without profile deviation or measurement noise. An improvement of this method has been presented in [9]. By taking advantage of the geodesic distance metric properties, Radvar-Esfahlan *et al.* [10] proposed the Generalized Numerical Inspection Fixture (GNIF) algorithm. An improvement of their method has been presented in [11]. In 2013, Wen *et al.* [12] presented an evaluation of freeform surface profile error based on Quasi Particle Swarm Optimization algorithm (QPSO) to implement the localization between the Measurement Coordinate System (MCS) and the Design Coordinate System (DCS), and on a surface subdivision method to search the closest points on the design model corresponding to the measured points. Furthermore, Aidibe and Tahan [13] developed in 2014 a new fixtureless inspection method for compliant parts by combining the curvature estimation with the Thompson-Biweight test as identification module. In their work, they proposed a new method to quantify the flexibility/rigidity of a given industrial compliant part. The proposed quantification method will allow industries to properly classify their mechanical components and will be strongly useful during tolerancing operations. They categorized non-rigid parts into three different categories.

Fig. 1. Aircraft skin panel conformed on a specialized jig

Zone A for the rigid parts where the displacement induced by a reasonable force during inspection is less than 10% of the parts' assigned profile tolerance. **Zone B** for the compliant parts. Parts classified in this zone are the most problematic to manage with regards to the specification, tolerance, and inspection of their geometric and dimensional requirements. By applying a certain amount of force, these parts get closer to the third zone. Finally, **Zone C** for the very flexible parts. In this zone very large deformations are produced just by the effect of the gravity (such as textile, human tissue, vessels, etc.).

There are many registration algorithms that offer robust and fast solutions they are adapted to parts located in Zone A and Zone C cases. For example, the Iterative Closest Point (ICP) algorithm developed in 1992 by Besl and Mackay represents one of the most important 3D rigid matching registration techniques [14]. It works very well with rigid parts located in Zone A. On the other side, the Coherent Point Drift (CPD) algorithm developed by Myronenko and Song [15] and widely used in the medical registration domain, works well with the very flexible parts located in Zone C. But these algorithms do not match with the alignment problems of relatively compliant parts located in Zone B.

Section 2 of this paper proposes a new approach to fixtureless inspect flexible parts located in the Zone B. The approach aims to develop a 'flexible registration' that retains the preservation of curvilinear distances (geodesic) while taking into account the presence of manufacturing profile [⌓,⌒] defect areas on the inspected part.

2. Methodology

Originally, the CPD algorithm includes two hyper parameters λ and β which are set manually [15]. Both parameters reflect the amount of smoothness regularization. Parameter β controls the rigidity and the locality of spatial smoothness while parameter λ reflects its strengths. The proposed approach consists of an optimization of the regularization parameters in order to adapt the CPD algorithm to the problem of relatively flexible parts as mentioned in the introduction.

In other words, this paper proposes to automatically estimate parameters λ and β by an iterative process that decides how much smoothing is necessary and how wide the range of interaction should be with respect to certain specific distance criteria. These criteria belong to relatively compliant parts (Zone B) and they are described in Fig. 3. The proposed method main steps are presented in Fig. 2.

The approach is started by initializing λ and β. Typically $\lambda_0 \in [1 \quad 50]$ and $\beta_0 \in [1 \quad 20]$.

Let $S = \{s_1, s_2, s_3, \dots, s_n | s_j \in \mathbb{R}^3\}$ be the set of n nodes representing the meshed CAD model and $P = \{p_1, p_2, p_3, \dots, p_m | p_j \in \mathbb{R}^3\}$ be the set of $m \mid m \gg n$ nodes representing the scanned part. The ICP algorithm is used in order to prealign the two given point sets in a common coordinate system (step 1 – Fig.2).

The CAD model is smoothly modified by the CPD to fit the scanned part respecting two criteria that belong to non-rigid parts (steps 2, 4 and 5 – Fig.2).

The first criterion Δ_{Str} is the condition that stretch difference should be very small between the original CAD model and the modified one (Fig 3a).

The second criterion Δ_D is the Euclidian distance between the modified CAD model and its corresponding scanned part (Fig. 3b).

$S' = \{s'_1, s'_2, s'_3, \dots, s'_n | s'_j \in \mathbb{R}^3\}$ is the set of n nodes resulting from this alignment. A *dsearchn* function in Matlab® based on Quickhull [16] is used to find C which is the set of n nodes representing the closest point in P to S' (step 3 – Fig. 2).

Parameters λ and β are then optimized by minimizing the proposed objective function that combines the normalized root mean square of the two described criteria as shown in equations 1, 2, 3 and 4. The detailed explanations with equations are provided in Fig. 3.

$$NRMS_{Str} = \frac{\sqrt{\frac{\sum\|\Delta_{Str}\|^2}{n-1}}}{\overline{Str_{S'}}} \tag{1}$$

$$NRMS_{D} = \frac{\sqrt{\frac{\sum\|\Delta_{D}\|^2}{n-1}}}{\overline{D_{C,S'}}} \tag{2}$$

Where $\overline{Str_{S'}}$ is the mean value of the stretch criteria of S' and $\overline{D_{C,S'}}$ is the mean value of the Euclidian distance between C and S'.

$$[\beta, \lambda] = \operatorname{argmin} F(\beta, \lambda | C, S, S') \tag{3}$$

Where

$$F(\beta, \lambda | C, S, S') = 20\times NRMS_{Str} + NRMS_{D} \tag{4}$$

Iteration (i) ends when the last step is smaller than a termination tolerance (ε) on the function or when the maximum number of iteration $(MaxIter)$ is reached. The optimal parameters β_{opt} and λ_{opt} will be used to output the corresponding final transformation parameters as computed by the CPD algorithm.

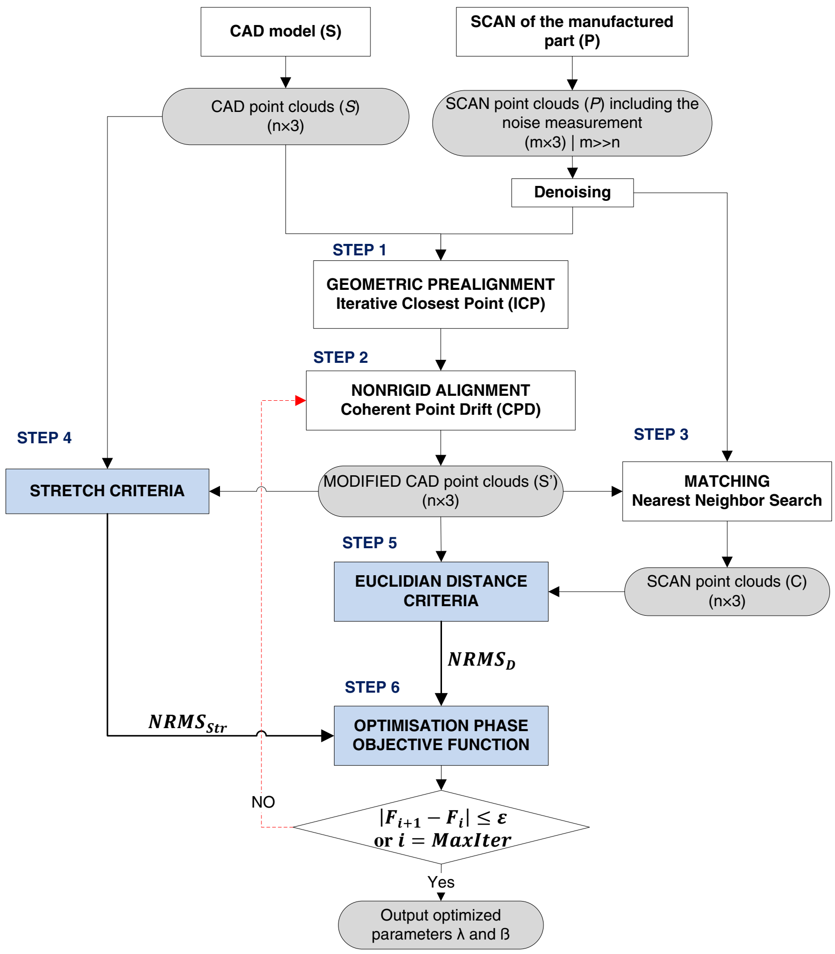


Fig. 2. Main steps of the proposed method

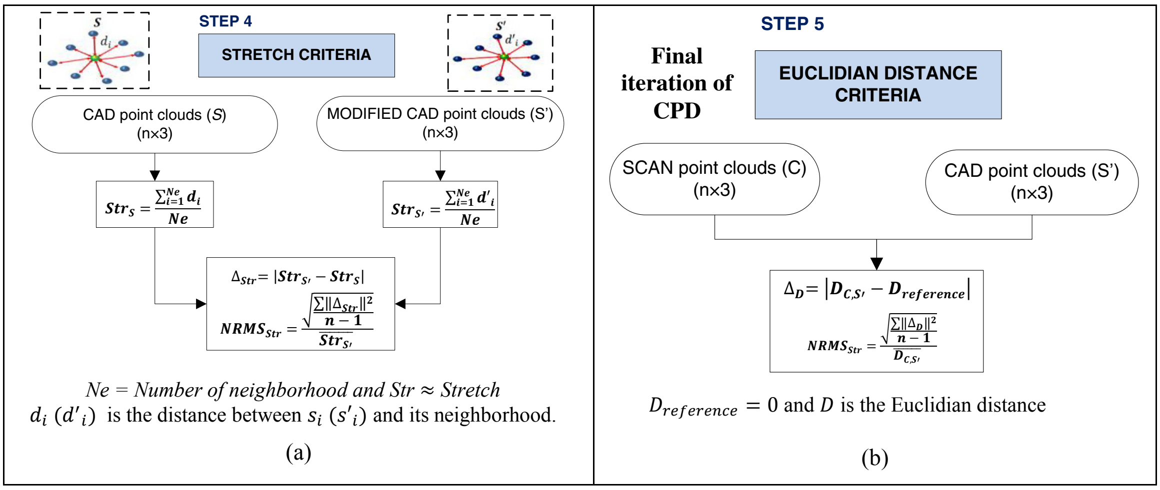


Fig.3 Developed criteria belonging to non-rigid part: (a) Stretch criteria (b) Euclidian distance criteria

3. Case studies

3.1. Description

In this section, an industrial case study is performed to validate the proposed methodology.

The test panel represented in Fig. 4a is made with an aluminum gauge 14 (1.63 mm). The shape varies significantly from its corresponding nominal at Free State. Consequently, the part is mounted on a very complicated and specialized jig designed by the First Article Inspection (FAI) department at an industrial plan as shown in Fig. 4b. Fig. 5 and Table 1 describes the different positions of the imposed profile defects. V0 test is performed to ensure that the method does not induce a bias. In other words, no defects should be detected if there aren't any imposed defects in the simulation part. In addition, five additional tests (V1 to V5) are performed to validate the methodology.

The scanned parts are compared with their corresponding nominal models using the proposed method. All case studies are performed on an Intel Core i7, 1.73 GHz, 4.0 GByte using a 64 bit operating system. The optimization phase is performed using the constrained nonlinear minimization (fmincon) on a Matlab R2012b platform.

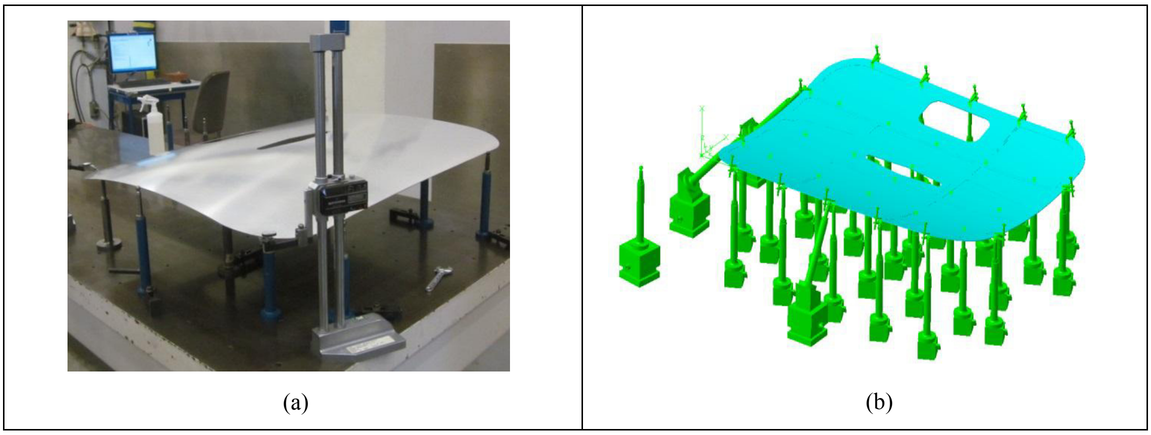
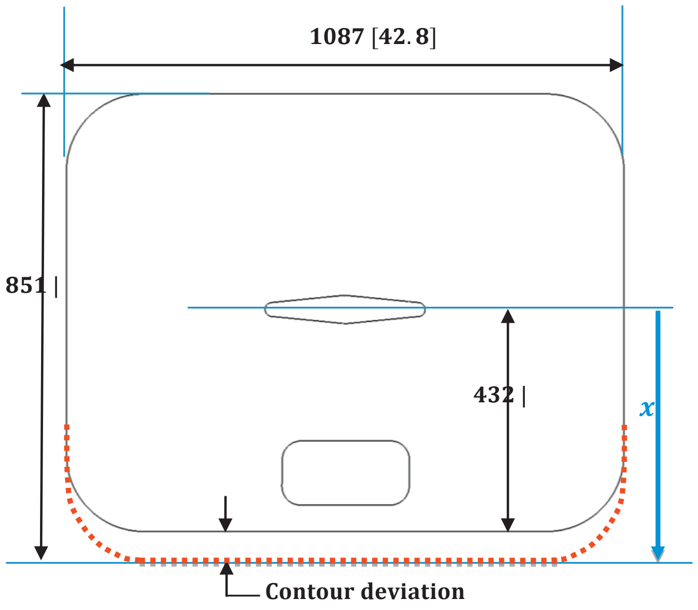


Fig. 4. Non rigid part case study: (a) at free state (b) at conformed state



All dimensions are in mm [$inch$]

Case Study		Size [n m] CAD SCAN	$Defect = x - 432$
A	V0	[4964 10046]	0[0]
	V1	[4964 10596]	2[0.078]
	V2	[4964 10800]	5[0.1968]
	V3	[4964 11046]	10[0.3937]
	V4	[4964 12489]	20[0.787]
	V5	[4964 14048]	30[1.1811]

Fig. 5. Non rigid part case studies description

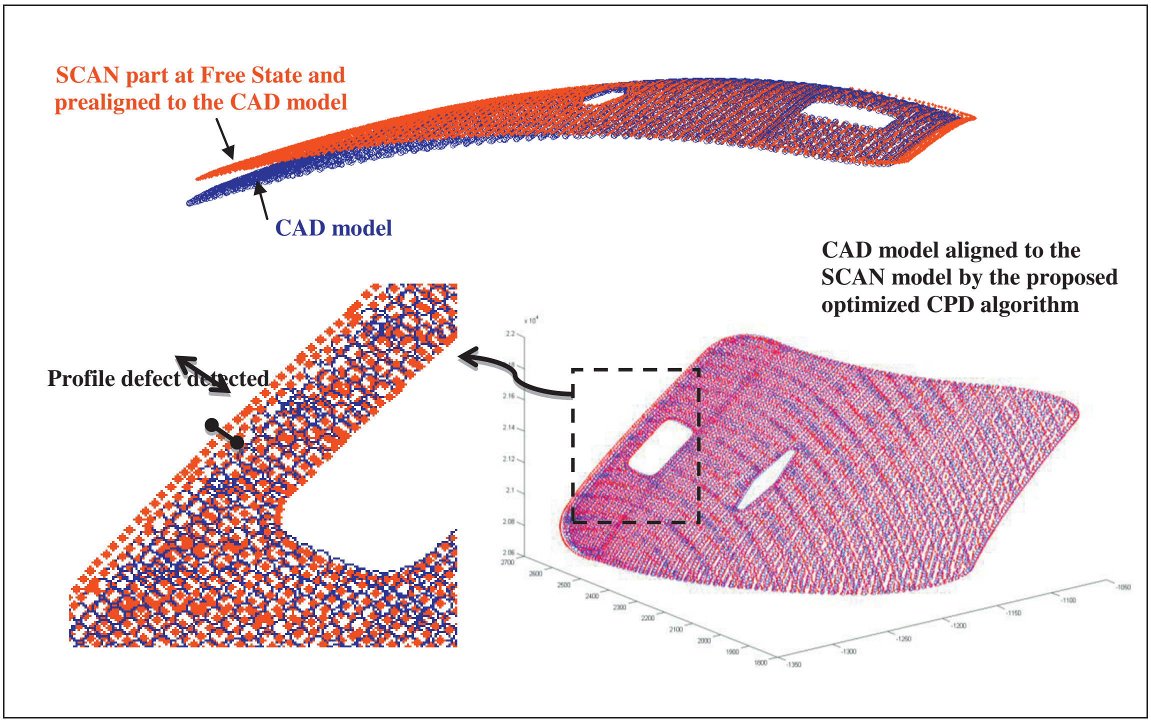


Fig. 6. Results of the proposed method

3.2. Results and discussion:

Analyzing Fig. 6 and Table 1, we can notice that:

- No defects are detected in the V0 case and this ensures that the proposed method does not create a bias.
- Using the proposed optimized coherent point drift algorithm, the nominal model is well-aligned to its corresponding scan in all cases.
- Table 1 shows that the estimated values of the profile defects are much closer to the reference ones in all cases.

Table 1. Results of the proposed method

Case		β λ	Nominal value Defect	Estimated value Defect
A	V0	3.9 8.2	0[0]	0[0]
	V1		2[0.078]	1.476[0.14]
	V2		5[0.1968]	4.13[0.284]
	V3		10[0.3937]	8.94[0.7]
	V4		20[0.787]	19.46[1.11]
	V5		30[1.1811]	29.68[1.396]

These results prove that the proposed method achieves acceptable results in the detection of the value and the position of the manufacturing profile defects.

4. Conclusion

Fixtureless metrology of non-rigid parts which is still a real problem for the transport industry, specifically the aerospace one, is presented in this paper. Dealing with this problematic, a new method is developed to inspect non rigid parts without specialized fixtures. Two criteria that belong to the specifications of non-rigid parts and an optimization of the CPD' regularization parameters to satisfy these criteria are developed and described in this paper. The results show that the proposed method is useful in the detection of the positions and the values of the defects. The profile defects estimated results in five different industrial case studies present closer values to the reference ones, thus reflecting the effectiveness of the proposed approach. Future research is underway to improve the performance of the proposed methodology and to validate it on other experimental case studies with different type of defects (for example, dimensional defects).

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